Project ID: mat189

2020 DOE Vehicle Technologies Office Annual Merit Review Presentation

Fundamental Development of Lightweight Alloys for Additive Manufacturing*

** Subtask 3A1 under the Powertrain Materials Core Program (PMCP)*

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Other contributors: Amit Shyam (Co-PI), Ryan Dehoff, Ying Yang, Sumit Bahl, Kevin Sisco, Larry Allard

Oak Ridge National Laboratory

June 4, 2020

Program Overview: VTO Powertrain Materials Core Program

Timeline/Budget

- Budget: $30M/5 years
- Program Start: Oct 2018
- Program End: Sept 2023
- 30% Complete

Barriers

- Increasing engine power densities & higher efficiency engines; resulting in increasingly extreme materials demands (increased pressure and/or temperature)
- Affordability of advanced engine materials & components
- Accelerating development time of advanced materials
- Scaling new materials technologies to commercialization

FY20 Program Research Thrusts	FY20 Budget	Participating Labs
1. Cost Effective LW High Temp Engine Alloys	$1.05M	ORNL
2. Cost Effective Higher Temp Engine Alloys	$1.525M	ORNL, PNNL
3. Additive Manufacturing of Powertrain Alloys	**$1.075M**	**ORNL**
4A. Advanced Characterization	$1.025M	ORNL, PNNL, ANL
4B. Advanced Computation	$0.60M	ORNL
5. Exploratory Research: Emerging Technologies	$0.75M	ORNL, PNNL, ANL

Partners

- Program Lead Lab
  - Oak Ridge National Lab (ORNL)
- Program Partner Labs
  - Pacific Northwest National Lab (PNNL)
  - Argonne National Lab (ANL)

Program structure includes three alloy development thrusts (1-3), a foundational support thrust (4), and a thrust for one-year exploratory projects (5).

Project Overview: Subtask 3A1

Timeline/Budget

- Project start: Oct 2018
- Project end: Sep 2022
- Percent complete: 37%
- **3A1 Budget**
  - **FY19: $300k**
  - **FY20: $425K**

Barriers

- New, alloys tailored for additive manufacturing (AM) are needed - very few commercial alloys available for AM
- Cost and scaling barriers for AM
- Little prior work on high temperature lightweight alloys via AM
- Development time. Project leverages an *Integrated computational materials engineering* (ICME) framework to reduce the early & mid-stage development time of new LW alloys by 50%.

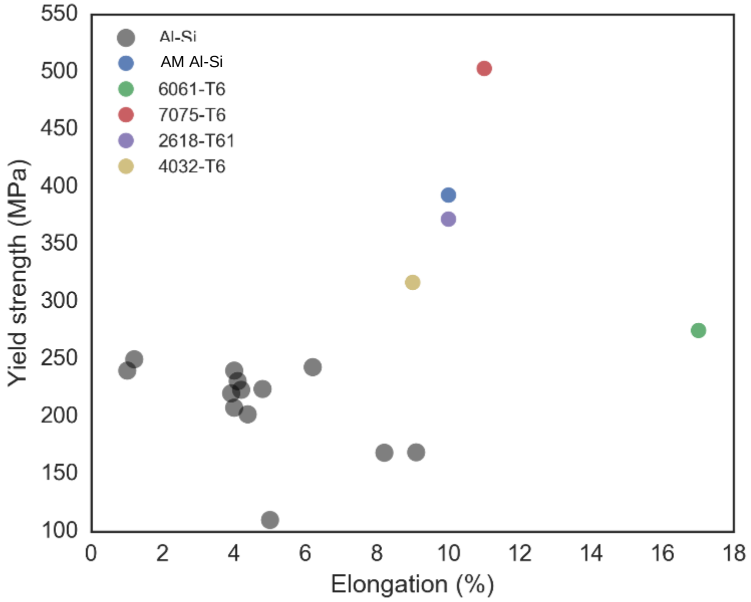
Thrust 3: Tasks/Subtasks	Lab	TRL	PI(s)	FY19	FY20
Task 3A. Fundamental Development of Lightweight Alloys for AM					
• 3A1. Fundamental Development of Lightweight Alloys for AM	**ORNL**	**Low**	**Plotkowski Shyam**	**$300k**	**$425k**
• 3A2. AMIPC (hybrid manuf. of composites)	ORNL	Low	Splitter	$250k	$225k
Task 3B. Development of Higher Temperature Alloys for AM					
-• B1. Fundamentals of Austenitic Alloys by AM	ORNL	Low	Dryepondt	$200k	$200k
• 3B2. Ferritic alloys for HD Pistons via AM	ORNL	Low	Nandwana Elliot	$325k	$225k
			Subtotals	**$1,125k**	**$1,075k**

Partners

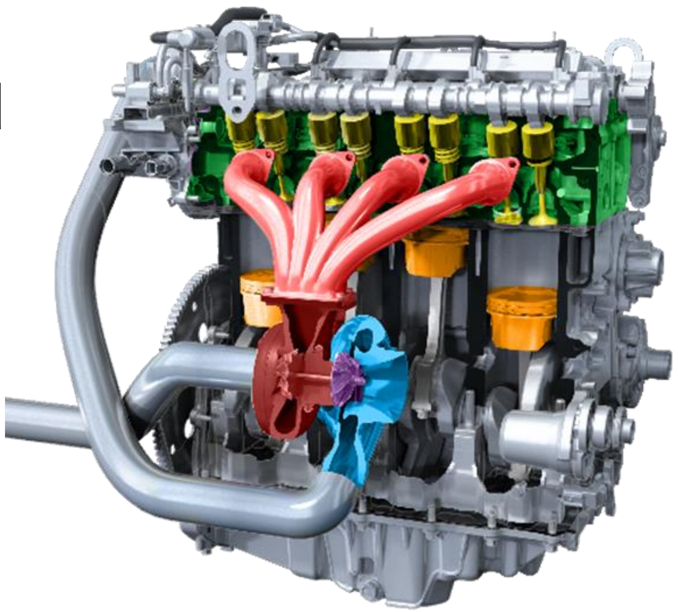
- Subtask 3A1 Lead
  - –Oak Ridge National Lab (ORNL)
- Subtask 3A1 Partners
  - –University of Tennessee
  - –Northwestern University
- Thrust 4
  - –Oak Ridge National Lab (ORNL)
  - –Argonne National Lab (ANL)
  - –Pacific Northwest National Lab (PNNL)

Relevance

- Power density of OEM engines have stagnated as the available alloys cannot meet the need for high-temperature (250-400°C) performance
- Metal additive manufacturing (AM) offers new design opportunities to improve performance, particularly for lightweight alloys such as Aluminum
  - Strong OEM interest
  - Powertrain applications (pistons, cylinder heads, turbochargers, etc.)
- But commercial aluminum alloy selection for AM is limited
  - Hot-tear susceptibility of conventional Al alloys
  - Poor high-temperature property retention
- **Design of new Al alloys for AM has potential to achieve unique microstructures and superior properties to improve engine performance and fuel economy**



Comparison of AM v. wrought properties (see alt-text)



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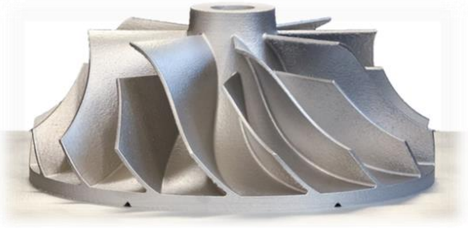
Milestones

Fundamental Development of LW Alloys for AM

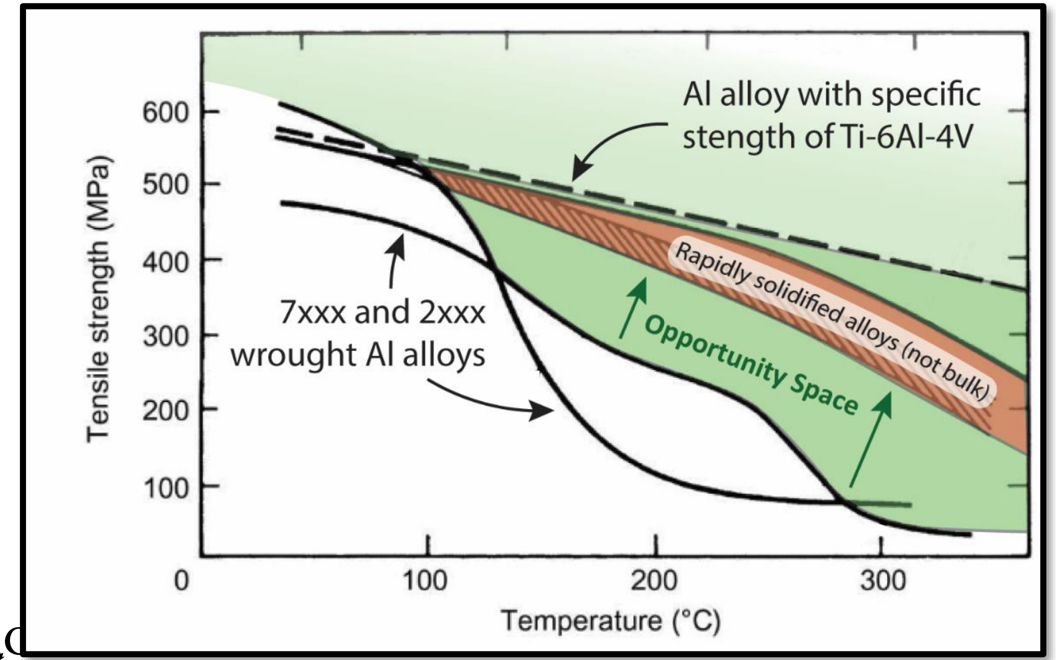
- **FY20 Q1 (3A1): Submit manuscript on the structure and high temperature properties of new, additively manufactured Al-Ce-Mn alloy COMPLETE**

- **FY20 Q4 (3A1), Go/No go: Design, acquire custom powders and print four new higher temperature additive aluminum alloy compositions from Cu and/or Ce as the primary alloying additions ON TRACK**

Approach – Alloy Design Targets



New alloys designed for the **unique processing characteristics of AM** will simultaneously enable **new design concepts** and **improved properties** vs what can be achieved with conventional processing



Manufacturing Challenges

- **Solidification cracking** (*i.e.*, hot-tearing)
- **Vaporization loss** of volatile elements
- Increase in material **cost** over Al-Si alloys

Property Requirements

- **High-temperature** mechanical strength
- **Thermally stable** microstructure
- **Creep** and **fatigue** resistance

Approach – Alloy Design Strategy

Literature Review

- Learn from casting, welding, and rapid solidification communities
- Apply fundamental materials knowledge

Computational Thermodynamics

- Evaluate hot tearing criteria
- Understand phase evolution

Alloy Selection and Feedstock Production

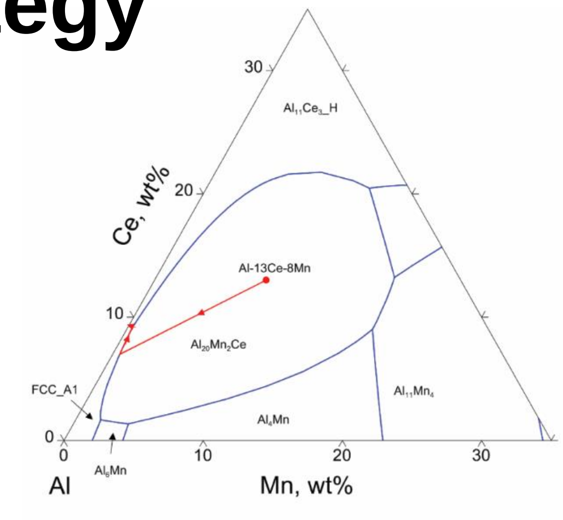
- Select alloy compositions to maximize information
- Key partnerships for complex powder feedstock production

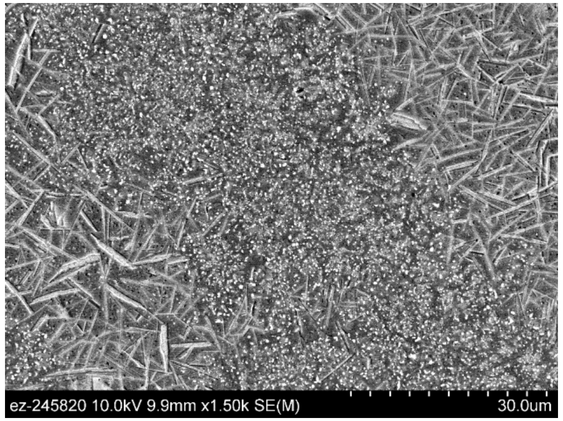
Rapid Process Optimization

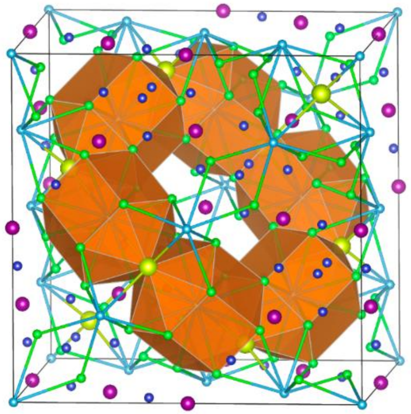
- Understand AM process characteristics
- Optimize process parameters

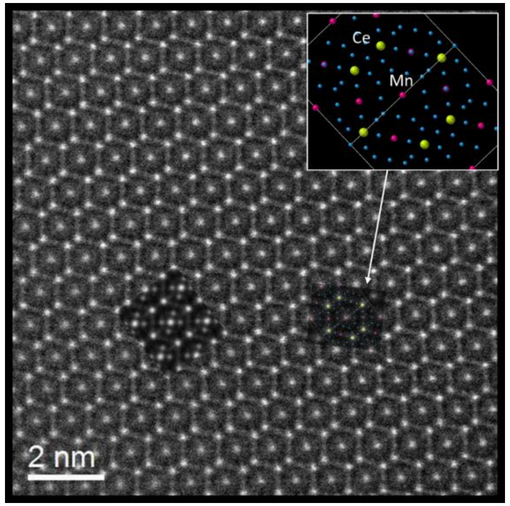
Testing and Advanced Characterization

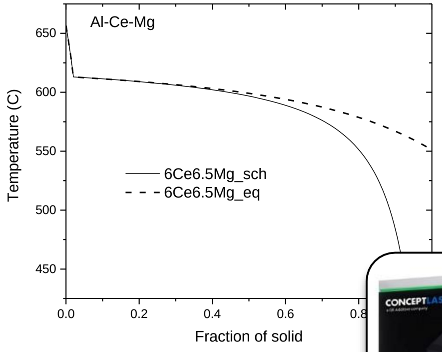
- Multiscale characterization
- Property testing







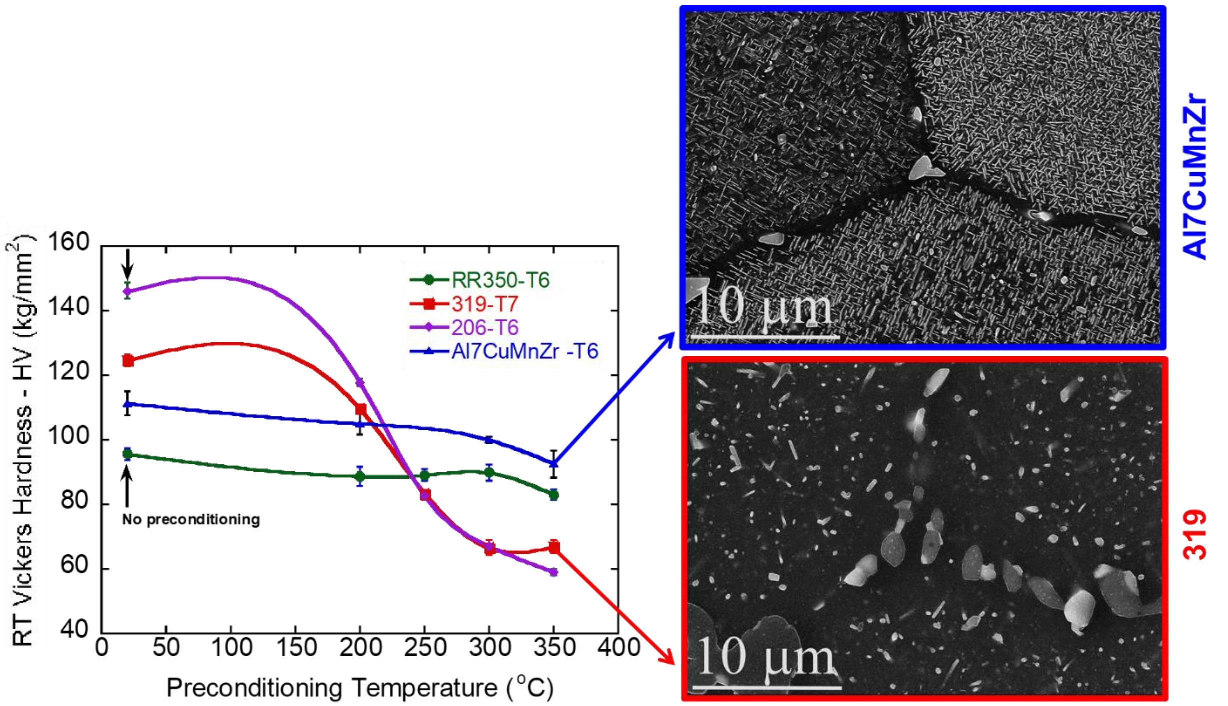




Laser powder bed fusion

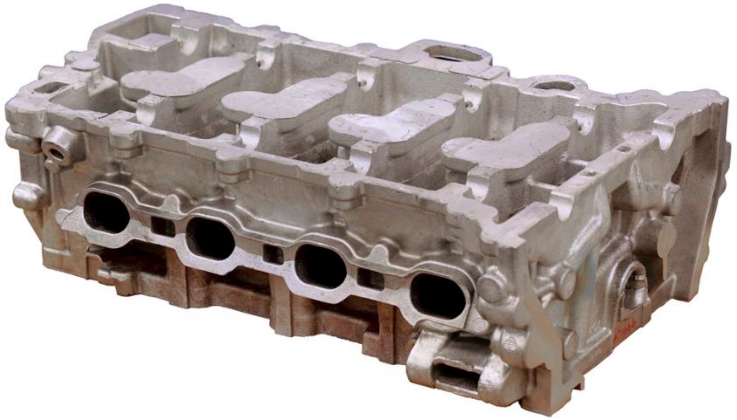
Previous Research on Cast Alloy Design

- Design of a castable Al-Cu based alloy with thermally stable mechanical properties at 300°C
- Developed Al-Cu-Mn-Zr (ACMZ) class of alloys
- R&D 100 award
- Industrial trials – FCA cylinder heads

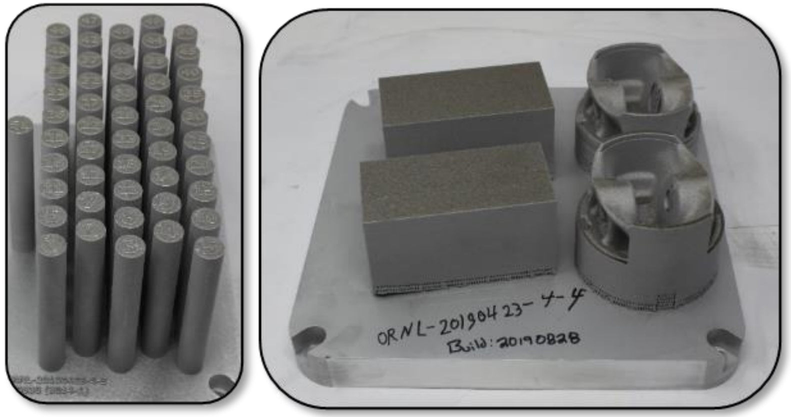


FCA
FIAT CHRYSLER AUTOMOBILES

Nemak

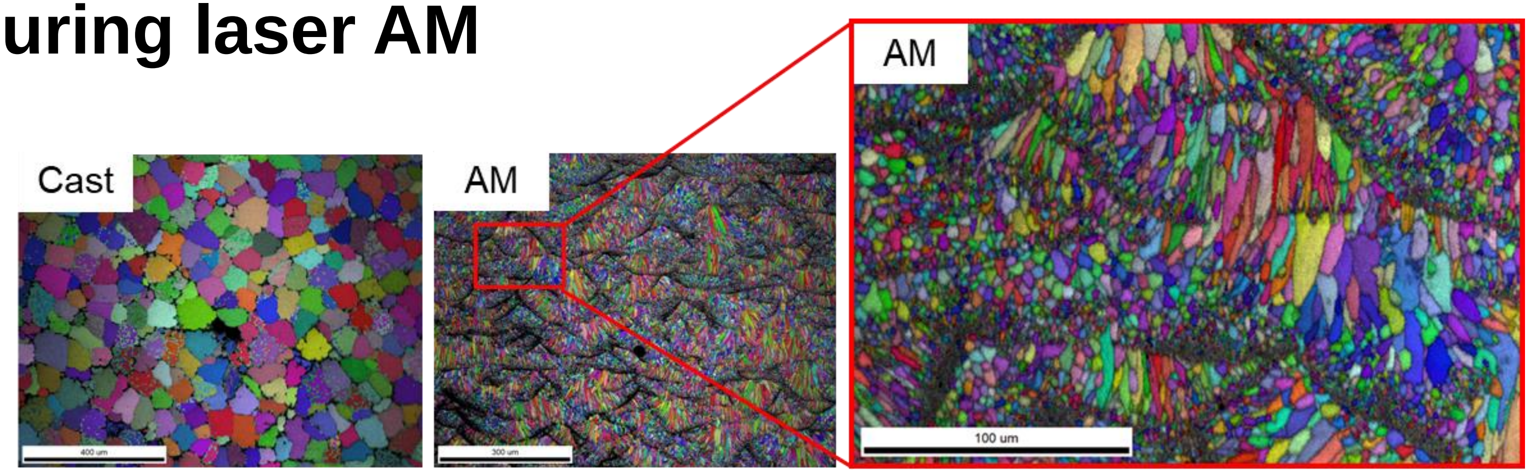


Technical Accomplishments and Progress

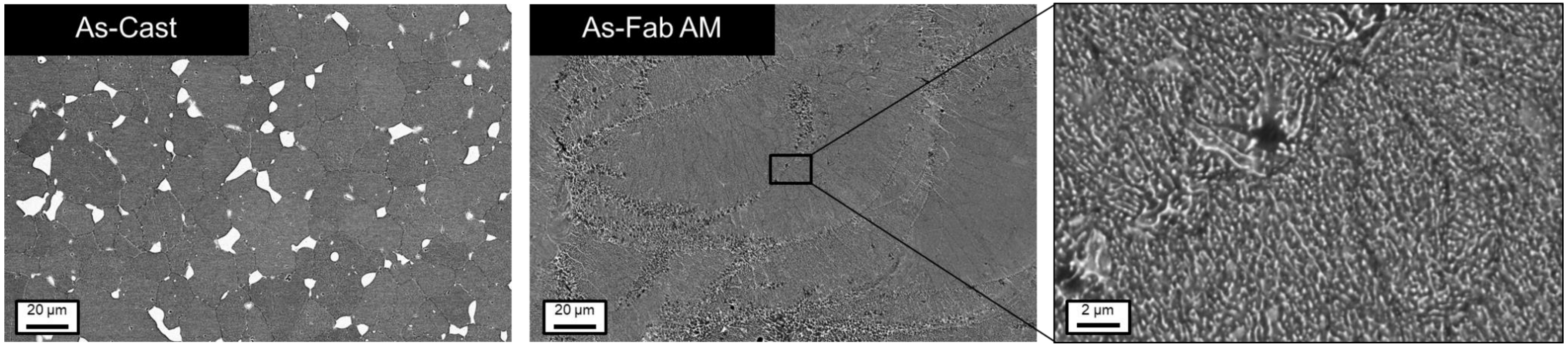


- Successful additive manufacturing of ACMZ alloy
- Microstructure is fundamentally different from conventional processing due to **rapid solidification conditions during laser AM**

Highly refined bimodal grain structure with grain refinement at melt pool boundaries from Al_3Zr particles acting as nucleation sites

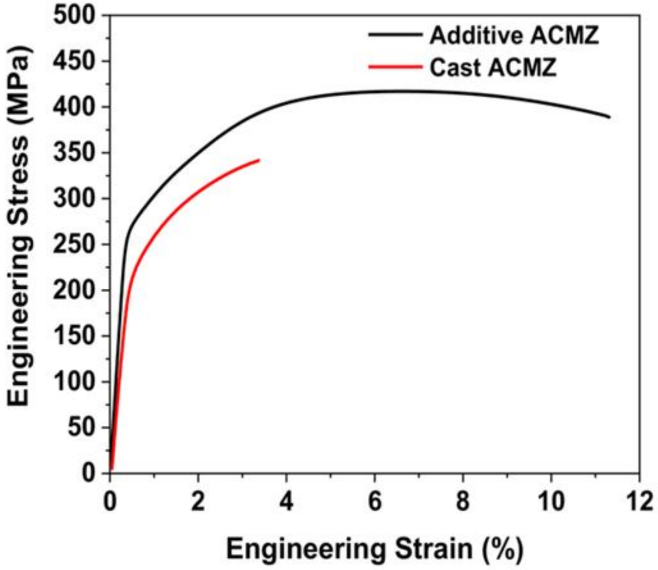


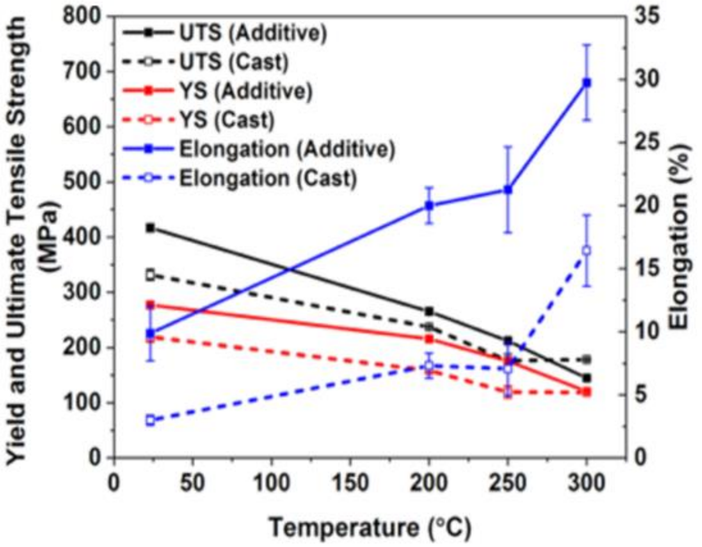
Al_2Cu θ particles are extremely fine and distributed throughout the microstructure rather than forming at grain boundaries

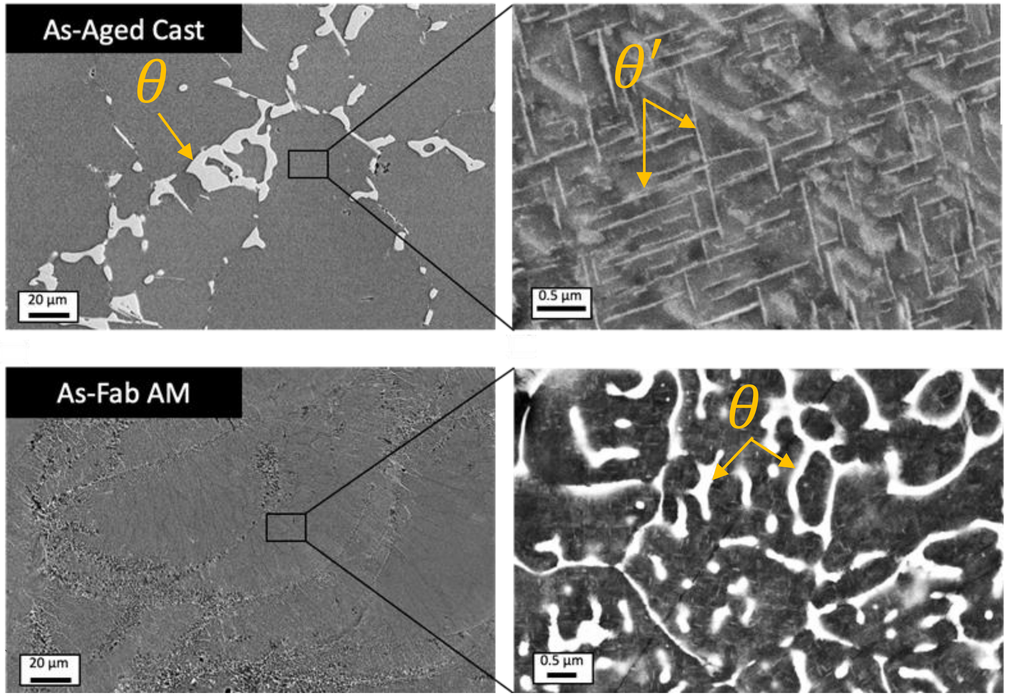


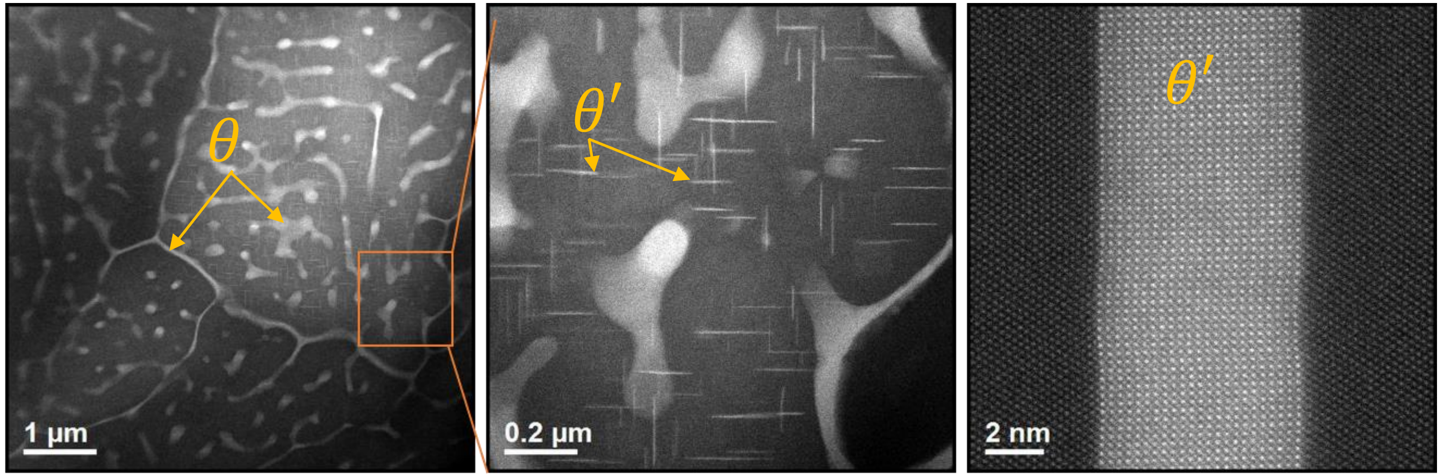
Technical Accomplishments and Progress

- Unique AM microstructure leads to superior mechanical properties
- As-fabricated mechanical properties of ACMZ show **both increased strength and ductility** compared to peak-aged cast material





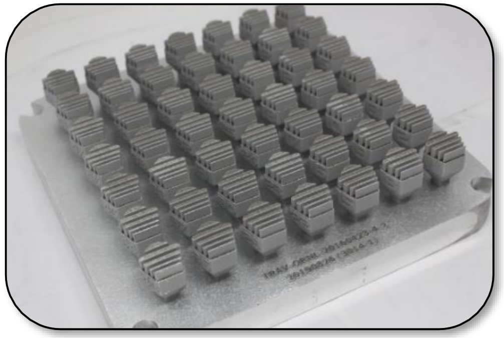




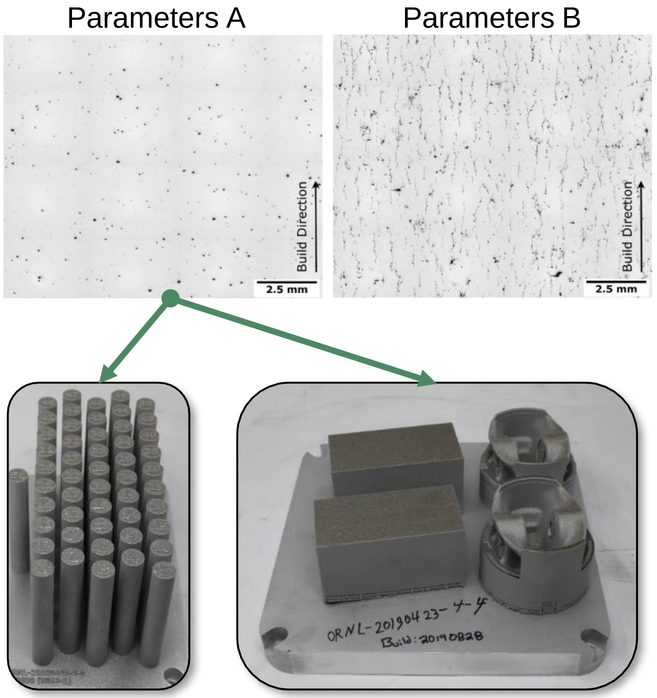
Technical Accomplishments and Progress

- ACMZ alloy is castable, but still prone to hot-tearing during AM, so **processing range is narrow**
- Hot-tearing is a function of both alloy composition & process conditions
- There is a need to **develop alloys with wide processing plateaus**
- Available models may be used to assess hot tearing relative to alloy composition

ACMZ - DoE

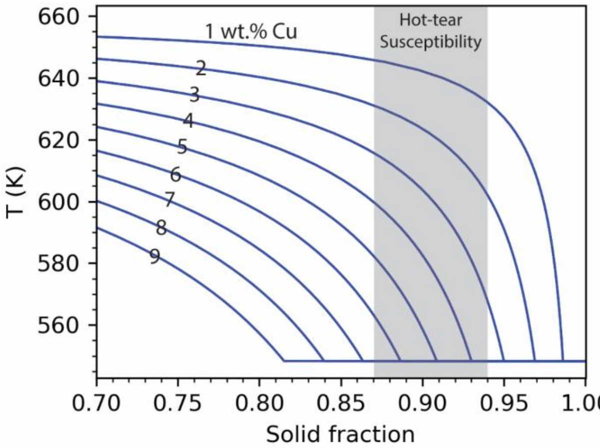


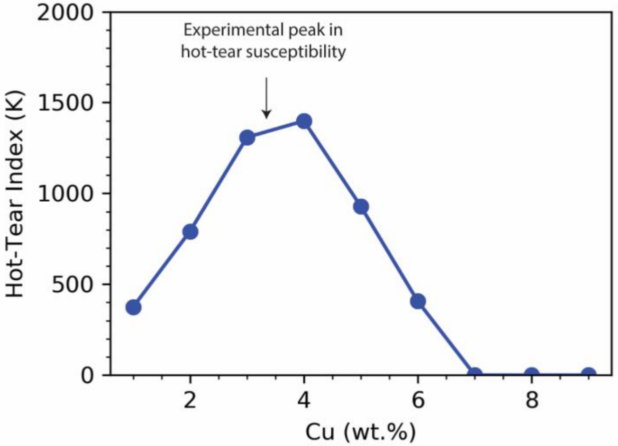
Design of experiments to identify crack-free process conditions



$$C_{Kou} = \frac{1}{\Delta f_s} \int_{0.87}^{0.94} \left| \frac{\partial T}{\partial \left(f_s^{1/2} \right)} \right| d f_s$$

Kou, Acta Mat., 2018.

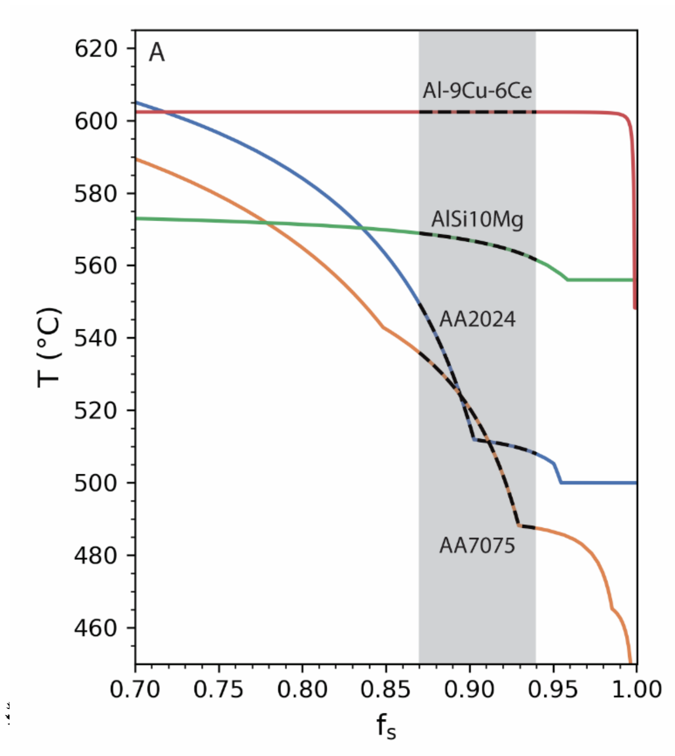




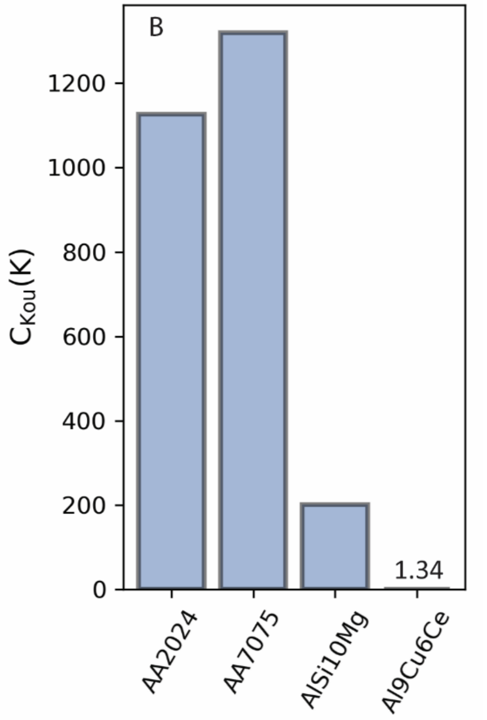
Simple model proposed by Kou. Explains peak in hot tear susceptibility of Al-Cu and Al-Si alloys.

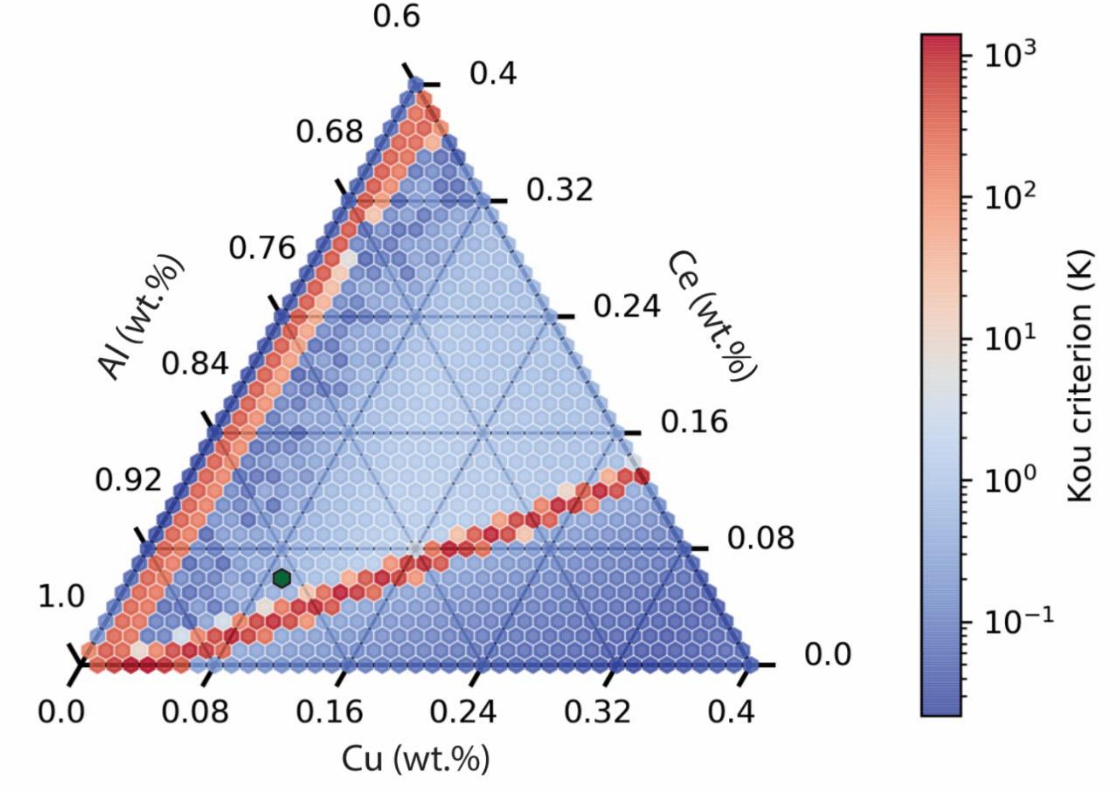
Technical Accomplishments and Progress

- Our newly developed Al-Cu-Ce based alloys have low hot-tear susceptibility compared to wrought alloys & even to the commercial AlSi10Mg alloy most commonly used for laser AM
- Using high-throughput computational thermodynamics models, we have mapped the hot-tear susceptibility through the Al-rich corner of the ternary system to aid in alloy design



Hot-tear susceptibility index



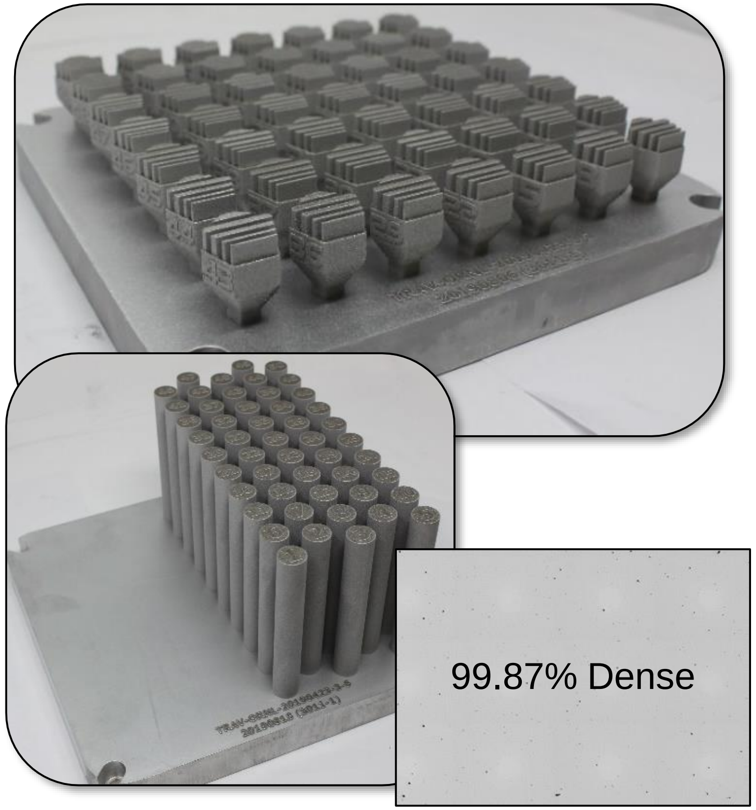


Technical Accomplishments and Progress

Designed three alloys in the Al-Cu-Ce system for **excellent printability** and **combinations of strengthening mechanisms**:

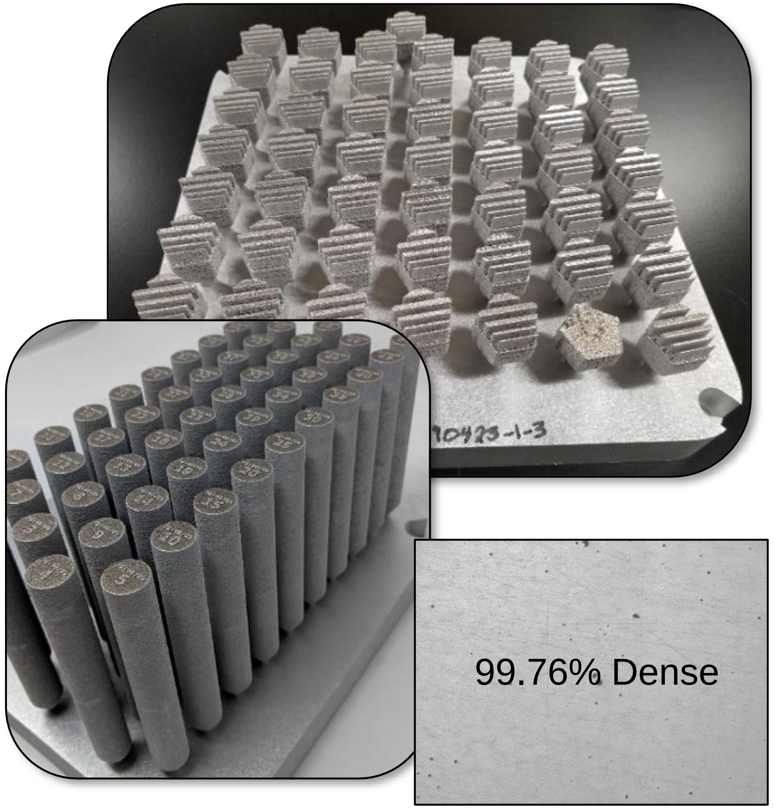
- Al-Ce-Cu system shows excellent hot-tear resistance
- Zr addition further improves hot-tear resistance through grain refinement, and offer precipitation hardening
- Mn added for solid solution strengthening

Al-9Cu-6Ce



Al-9Cu-6Ce-**1Zr**

Al-9Cu-6Ce-**1Zr-0.5Mn**



Technical Accomplishments and Progress

Al-Cu-Ce

- Excellent hot-tear resistance
- Good thermal stability up to 250°C
- Decrease in RT hardness at higher temperatures

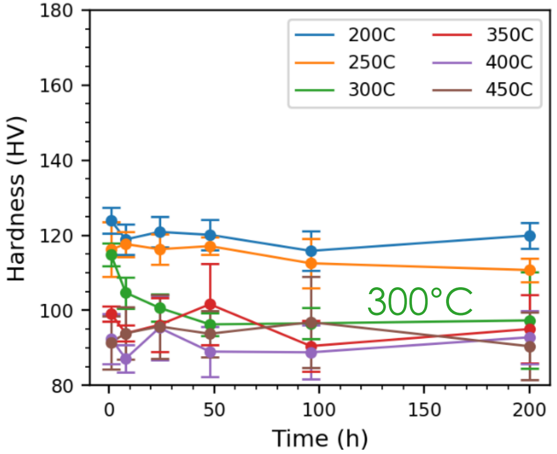
Al-Cu-Ce-Zr

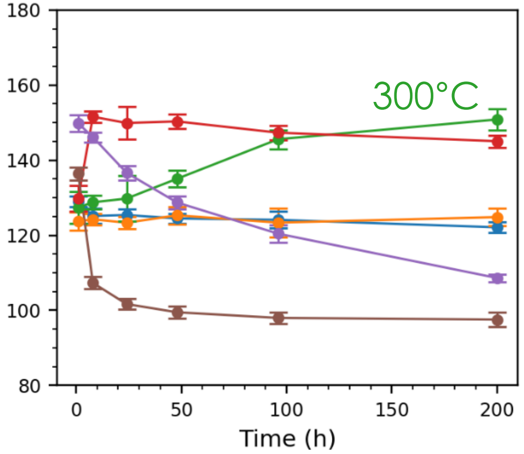
- Even better hot-tear resistance from Zr grain refining effect
- Increase in hardness up to 350°C due to Zr precipitation

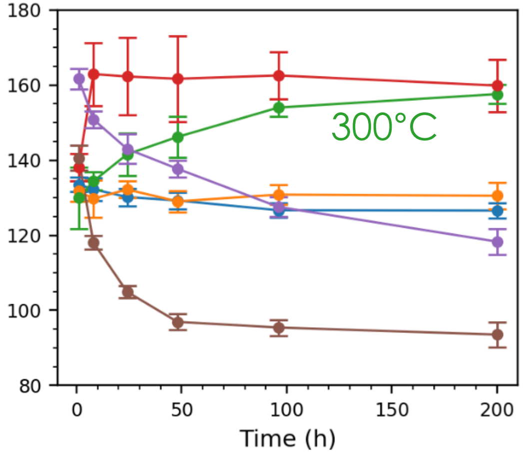
Al-Cu-Ce-Zr-Mn

- Mn degrades hot-tear resistance
- Good precipitation response from Zr
- Additional hardness increase from Mn solid-solution strengthening

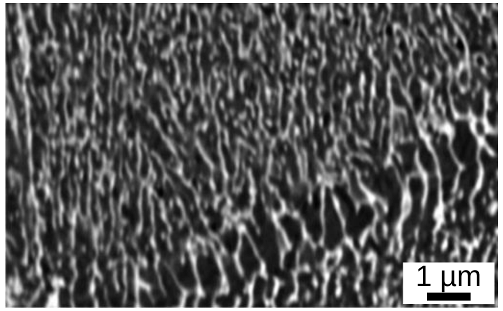
RT Hardness after Thermal Exposure

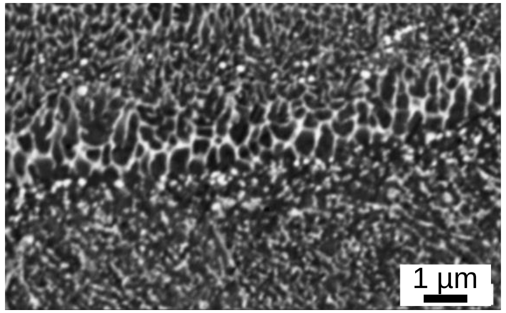


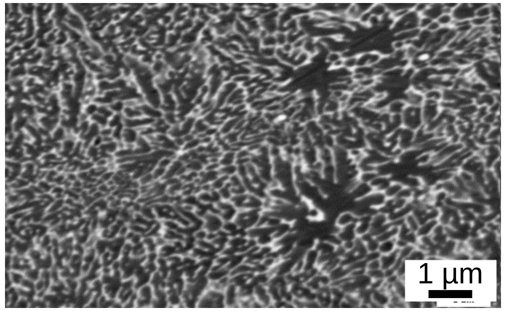


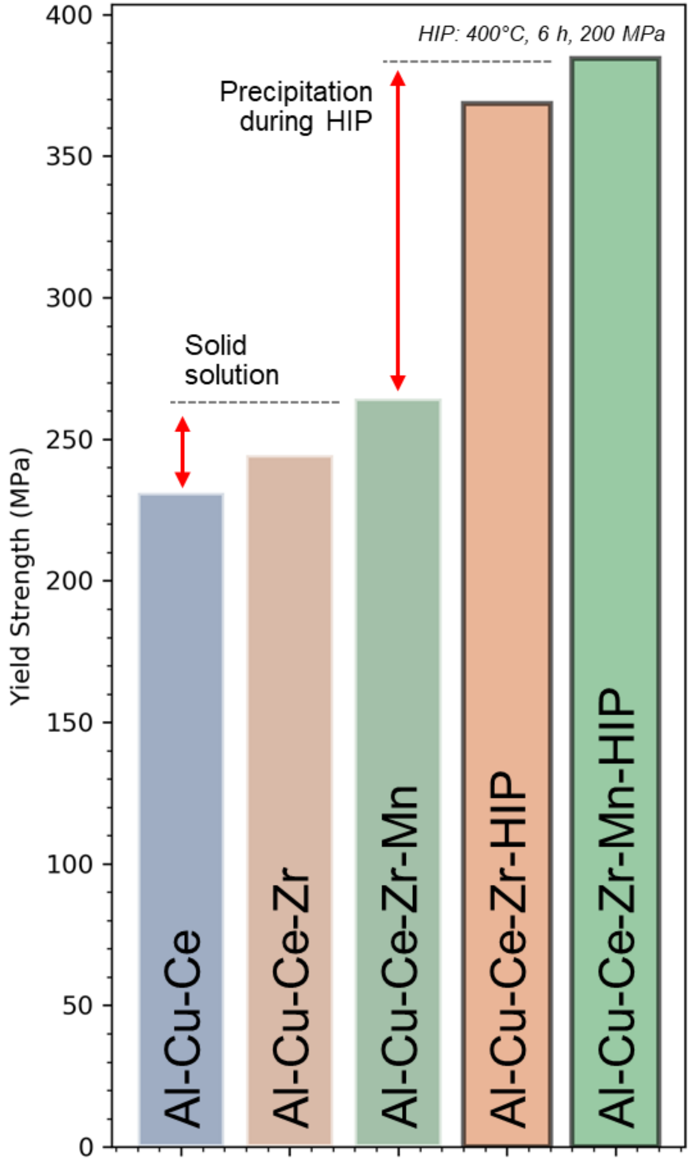


Representative Microstructure



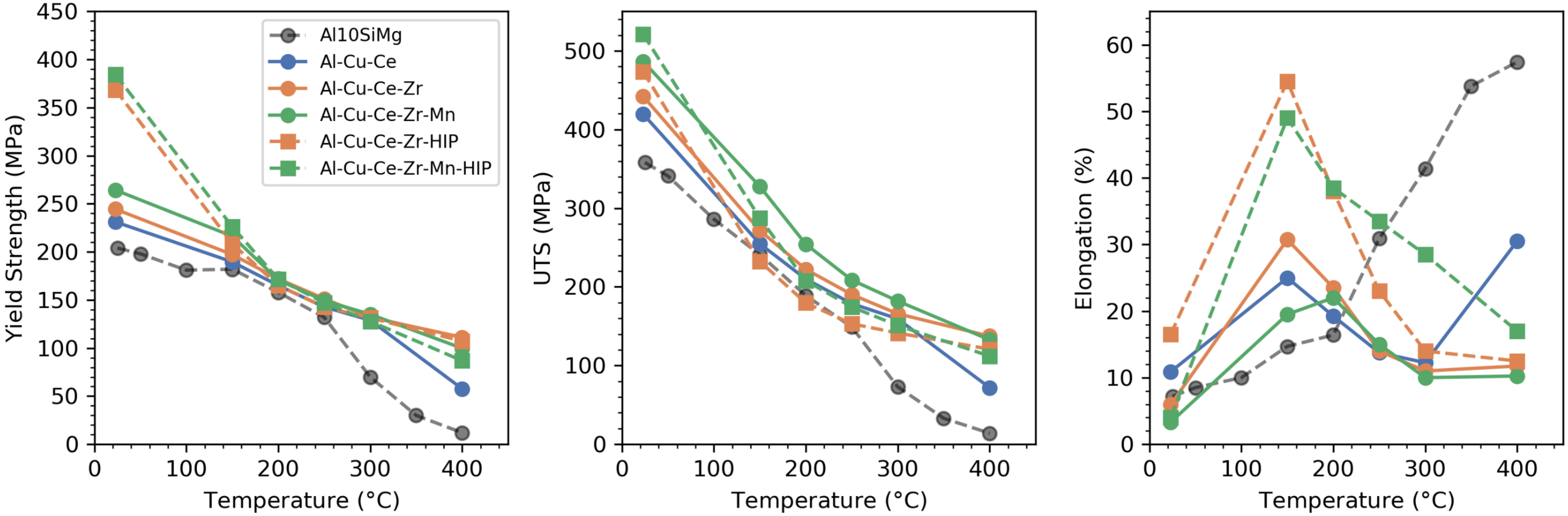






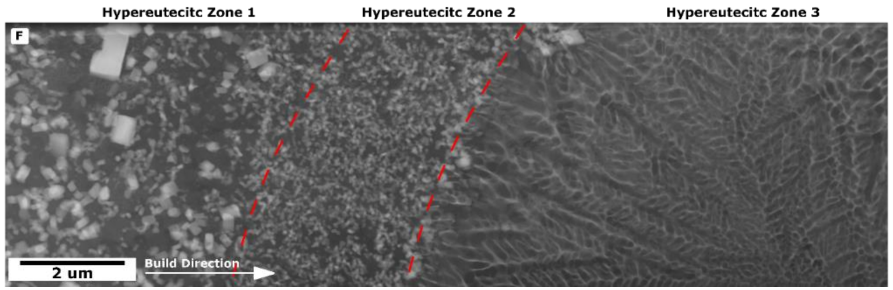
Technical Accomplishments and Progress

- Tensile properties show a <u>significant</u> improvement over what can be achieved with printable Al10SiMg based commercial alloys
- Improved strength retention at elevated temperature, particularly between 300-400°C

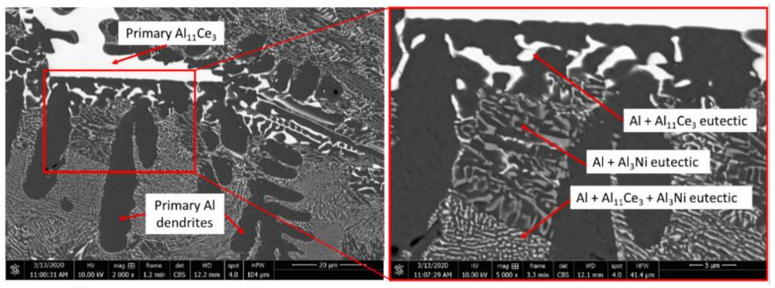


Collaboration and Coordination

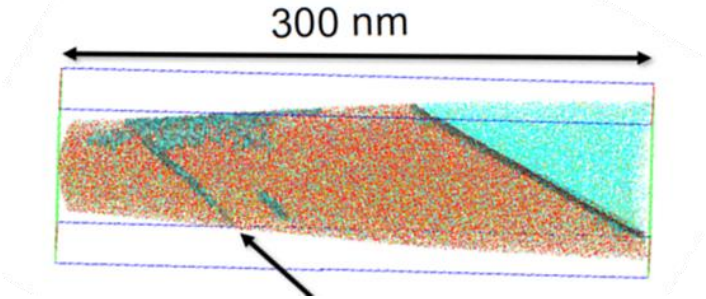
– University of Tennessee – Dr. Suresh Babu
  - Rapid process optimization and characterization



– Northwestern University – Dr. David Dunand
  - Microstructure and creep of AM eutectic Al alloys



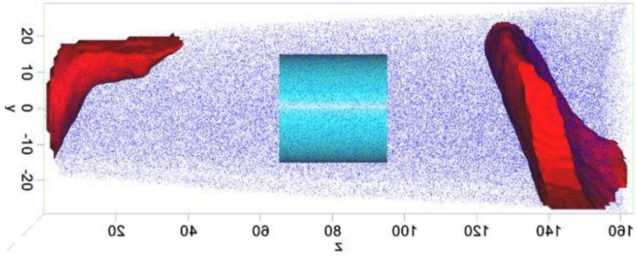
– University of Sydney – Dr. Simon Ringer
  - Advanced characterization of Al-Ce-Mn alloys



– University of New South Wales – Dr. Sophie Primig
  - Advanced characterization of Al-Cu-Ce alloys

– Thrust 4A: Advanced Characterization – Larry Allard

– Thrust 4B: Advanced Computation – Ying Yang

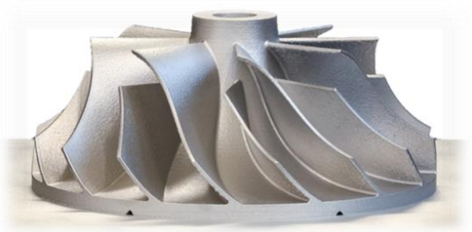


Remaining Challenges and Barriers

- Non-equilibrium solidification conditions
  - Solidification mode is not consistent with alloy thermodynamics due to high solidification rates and generates **novel microstructures**
  - These effects complicate interpretation of **hot-tearing criterion** based on Scheil simulations
  - Resulting microstructure gives **unique properties** that are not always analogous to cast counterparts, requiring **significant characterization** and expert interpretation
- Lead-time and expense for powder feedstock production
- *Response to previous year reviewers' comments:*
  - *Project was not reviewed last year*

Proposed Future Research

- FY20
  - Fabricating four additional alloy compositions
  - Alloys designed based on previous results
- FY21 and beyond
  - Alloy characterization to understand non-equilibrium microstructure evolution in response to AM processing
  - Codifying design rules for printability and high-temperature properties
  - Prototype components for powertrain applications
    - Pistons, cylinder heads, turbocharger components



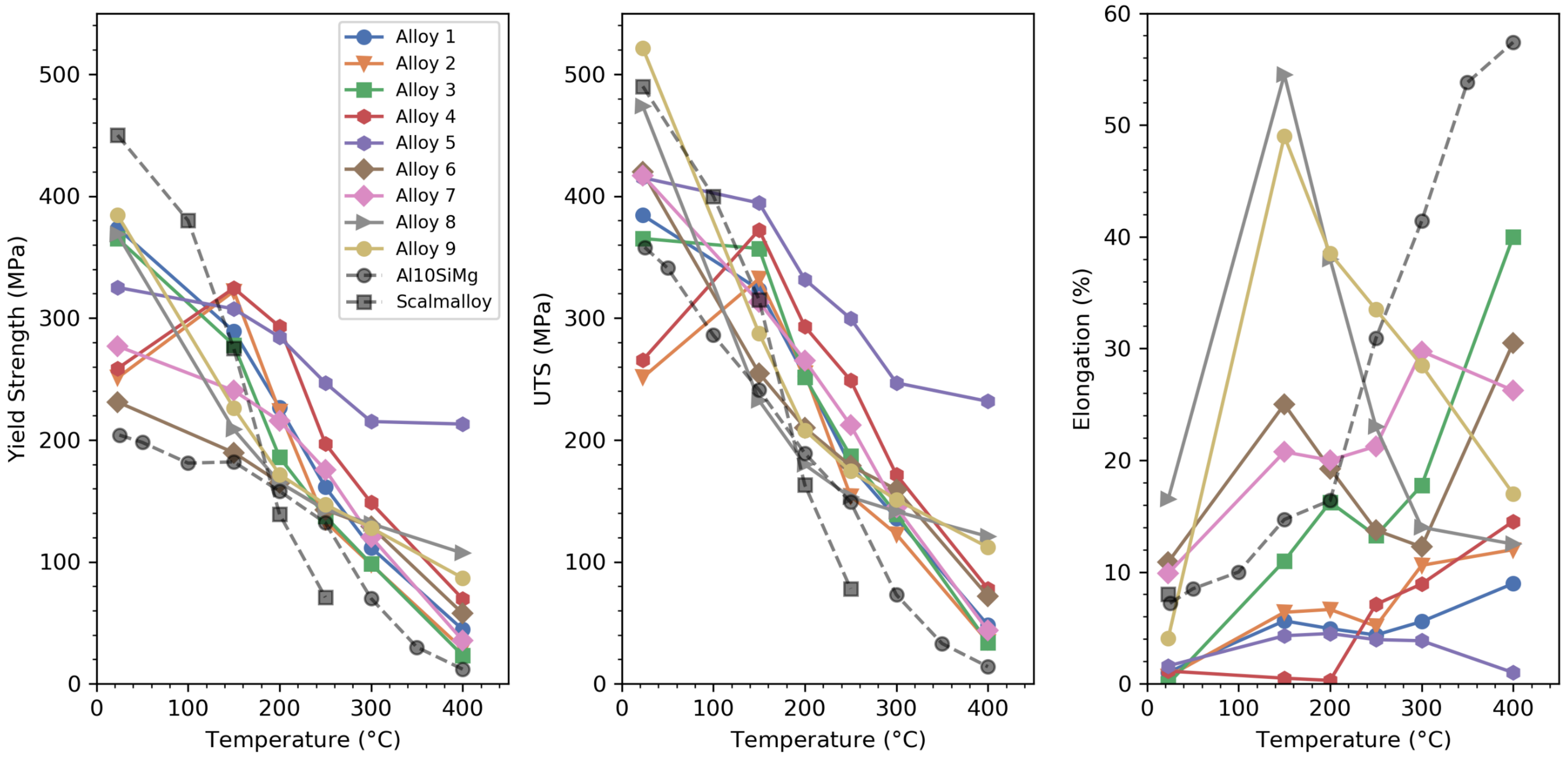
Any proposed future work is subject to change based on funding levels.

Summary

- Approach
  - Design new Al alloys for additive manufacturing to produce unique microstructures and superior property combinations
  - Targeting design toward resistance to hot-tearing and good high-temperature mechanical properties
- Technical Accomplishments
  - Demonstrated successful additive manufacturing of previously developed (for casting) AlCuMnZr alloy with mechanical properties superior to the peak-aged cast versions
  - Developed hot-tear resistant Al-Cu-Ce alloys with further improvements in printability
- Collaborators
  - University of Tennessee, Northwestern University, University of Sydney, University of New South Wales
- Future Work
  - Four additional new alloy compositions in development for FY20
  - Advanced characterization to understand non-equilibrium microstructure in AM
  - Pursuing opportunities for powertrain component prototyping and demonstration

Technical Back-Up Divider Slide

Technical Back-Up: Example Mechanical Properties



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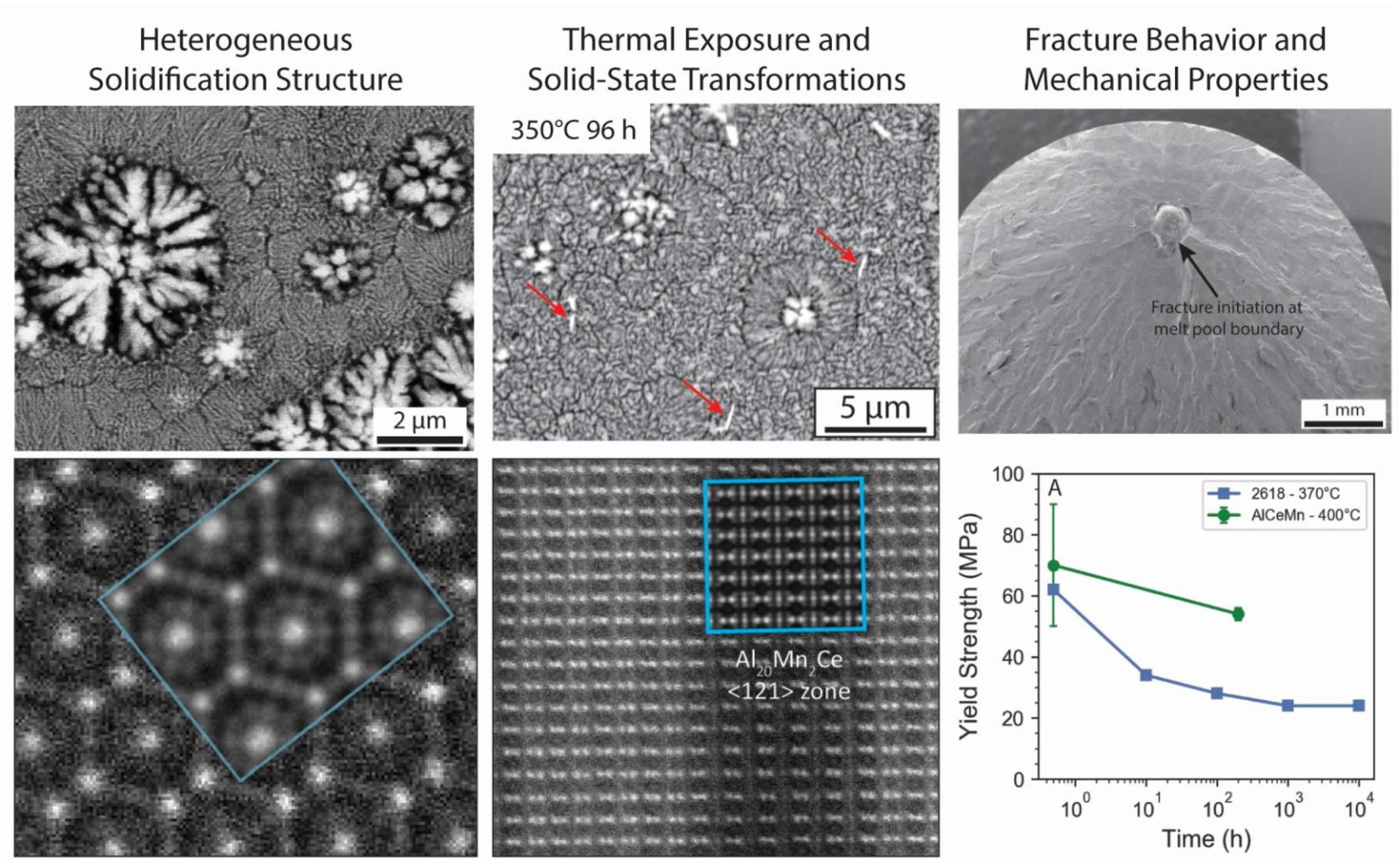
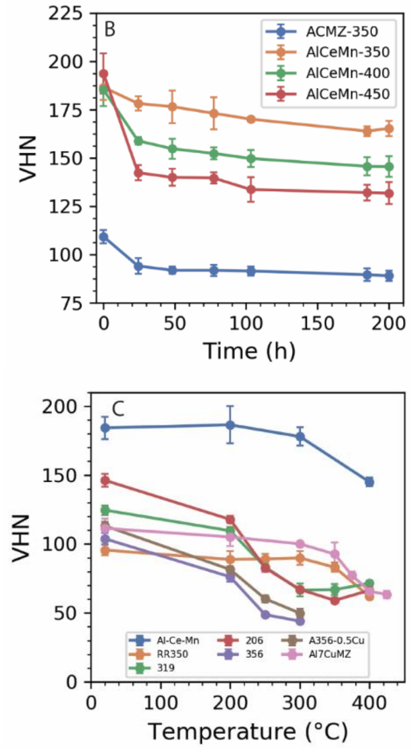
Technical Back-Up: FY20 Results – Submitted Publication on AM Al-Ce-Mn

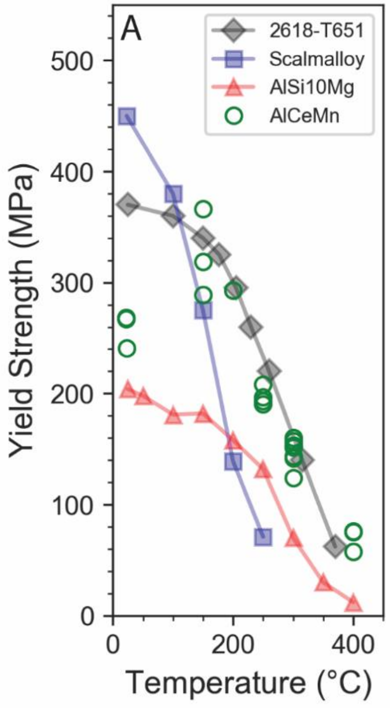
- In review at Acta Materialia



High hardness and thermal stability relative to cast alloys



Excellent high-temperature mechanical properties



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